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ADP011328

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TITLE: Display Technologies III Held in Taipei, Taiwan on 26-27 July 2000

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Simulation of Geometric Effects on Double-Gate Field Emission Devices

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ABSTRACT

We report a study of the circular-shaped and rectangular-shaped focus-gate Field Emission Devices (FED) structure. In this work, we have developed a simulator of FED based on the Finite Difference Method (FDM). The major element of this simulator is a modified Fowler-Nordheim (F-N) field emission model. We evaluate the performances of the circular-shaped and rectangular-shaped focus-gate FED structures by using this simulator. Results reveal that the circular-shaped focus-gate FED structure has more collector current. Also, the focusing characteristics of electron beam are improved.

Keywords: circular-shaped, rectangular-shaped, focus-gate, Field Emission Devices, simulator, Finite Difference Method, Finite Difference Method, Fowler-Nordheim, electron beam

1. INTRODUCTION

Field Emission Devices (FED) have many potential applications in Flat Panel Display (FPD)[1-3]. Field emission displays are increasingly becoming one of the significantly emerging candidates for the next generation technology of display due to lightweight, small volume, wide view-angle and low power. They are highly predicted to be commercially available in the near future. Nonetheless, there are many drawbacks of the FED, such as the phosphor power of exceptional materials, small collector current and low brightness. Many investigators have tried to improve these defects.

To improve the collector current and beam-focusing characteristics of FED and to obtain an optimized device structure, many investigators simulated the performances of FED[4]. Most investigators used Finite Element Method (FEM)[5] and Fowler-Nordheim (F-N) field emission model to simulate FED. However, the FEM consumes computation time of CPU. Therefore, we utilized Finite Difference Method (FDM) to compute the current—voltage relationships to accelerate computation time of CPU than FEM. Besides, the major elements of our simulator are a modified Fowler-Nordheim field emission model, electron-trajectory simulation in vacuum space (considering space charge effects) and the characteristic simulation of electrical performances. The procedure steps of the FED simulation include: (1) solving the two-dimensional Poisson equation, (2) calculation of the emitter-tips electric field (3) obtain the current density[6-8] by using the remarkable Fowler-Nordheim (F-N) tunneling formula. In addition, space charge effect[9-11] and emitter heating effect[12] have been considered in the simulation.

In this work, simulated electrical performances based on the geometric effects of different focus-gate structures have been systematically investigated. In addition, we will evaluate the performances of the circular-shaped and rectangular-shaped focus-gate FED structures by using this simulator. Finally, we will show the results of collector current and electron beam in vacuum space.

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In *Display Technologies III*, I-Wei Wu, Heiju Uchiike, Editor,
Proceedings of SPIE Vol. 4079 (2000) • 0277-786X/00/$15.00

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2. NUMERICAL MODEL AND SIMULATION METHODS

When an external electric field is applied to the surface of a metal, the potential barrier is lowered due to the Schottky effect. If the electric field exceeds the order of 1×10^{7} V/cm, field emission takes place.

A Fowler-Nordheim emission module was developed to model electron field emission from the surface. Emitted current density is determined from the Fowler-Nordheim equation, which has been expressed as:

$$J = \frac{AE^2}{\phi \cdot t^2} \exp\left(-\frac{B \cdot v(y) \cdot \phi^{3/2}}{E} \right) \qquad \text{Eq. (1)}$$

where $A = 1.5414 \times 10^{-6}$, E = the normal component of the electric field at the emitter surface, ϕ = work function of the emitter, taken as 4.35eV for Mo, $B = 6.8308 \times 10^9$, $t^2 \approx 1.1$, an approximation, and $v(y) = 0.95 - y^2$ with $y = 3.79 \times 10^{-5} \times E^{1.2}\!\!\Big/\!\phi$ in SI unit. Initially, the Green's function solutions of the Laplace equation are computed for the given geometry. The electric field along the emitter surface was determined by superposition of the contribution from each conductor.

After the emission current is evaluated, we perform the electron trajectory simulation. The reason is this simulation paves the way for the determination of the electron density distribution in vacuum.

Electron trajectory simulation is in the following. First, no scattering event occurs during the electron transport in vacuum. Second, the non-diversity property of electron motion in space is suggested. The electron distribution function drops rapidly with an increase of the transverse-part of electron energy if the longitudinal-part of electron energy is kept the same due to the Fermi-Dirac statistics. Only a small portion of the tunneling electrons has an extra velocity component in the transverse direction. So, the assumption of the non-diversity effect of the electron tunneling through the barrier can easily be justified. Eventually, the magnetic effect is neglected.

From the classical Newtonian mechanics, the equation for the motion of electrons in the vacuum region can be expressed as:

$$\frac{d\vec{r}}{dt} = \vec{v} \qquad \text{Eq. (2)}$$

$$m\frac{d\vec{v}}{dt} = e\nabla V \qquad \text{Eq. (3)}$$

where $\vec{r}$ and $\vec{v}$ are the position and the velocity of the electron, respectively, t are the time, e and m are the electron charge and mass, respectively.

The initial conditions imposed on this assumption are:

$$\overrightarrow{r(0)} = \frac{\int_{-E_f}^{\phi} [r_o(W_l)N(W_l)T(W_l)]dW_l}{\int_{-E_f}^{\phi} [N(W_l)T(W_l)]dW_l}\hat{n} \qquad \text{Eq. (4)}$$

$$\overrightarrow{v(0)} = \vec{0} \qquad \text{Eq. (5)}$$

where $r_o(W_l)$ is the tunneling distance of electron with the longitudinal-part of electron energy equal to W_l and n represents the unit vector which is normal to the emitter surface at that emission site. In addition, two kinds of boundary conditions, i.e., gate and collector, are employed. The total emitter-to-electrode current is computed by summing up all the

current elements, which are absorbed by the electrode. If the electrons arrive at a dielectric or vacuum boundary, the reflective boundary condition is applied for the same reason as we used in solving the 3D Poisson equation. Eq. (4) and Eq. (5) are then decomposed into six first order differential equation in the 3D Cartesian coordinate system. With the initial and boundary conditions, the fourth order Runge-Kutta method is applied to solve these six equations simultaneously. The position $\vec{r}$ and the velocity $\vec{v}$ of the emitted electrons can be easily obtained.

3. SIMULATION RESULTS AND DISCUSSION

The FED structures which includes a pyramid-like emitter, a control-gate electrode, an additional gate electrode (we call focus-gate), and a collector electrode is shown in Fig. 1. The control-gate controls the major current of tip emission[16]. Furthermore, the focus-gate is needed for focusing and accelerating emitted electrons.

We evaluated the performances of various focus-fate FED structures by using our simulator. Then, we will gain a physical insight into these devices by way of a series of analysis. Firstly, we discuss the results of current-voltage characteristic curves of the circular-shaped and rectangular-shaped focus-gate FED structure. Secondly, we will compare their electron trajectories. The effects of the focus-gate structure will be studied systematically. Finally, the dependence of collector current of the aperture of focus-gate will be investigated.

Fig. 2 shows the Current-Voltage characteristics curve of the circular-shaped and rectangular-shaped focus-gate FED structure. The collector and control-gate voltage are 1000V and 100V, respectively. As shown, the collector current of the circular-shaped focus-gate FED structure is larger than the rectangular-shaped focus-gate FED structure. Also, raising focus-gate bias of both FED structure can increase more collector current.

Fig. 3 (a)~(b) show the electron-trajectory simulation of different focus-gate structures. The applied biases of collector, control-gate and focus-gate are 1000V, 100V, and 10V, respectively. According to the simulation results of electron trajectory, we took advantage of circular-shaped focus-gate to control the electron trajectory of emitter, because it can significantly improve the focusing characteristics of electron beam.

Final, the dependence of collector current on the aperture of the circular-shaped and rectangular-shaped focus-gate FED structure is shown in Fig. 4. The biases of the control-gate, focus-gate and collector are 100V, 10V and 1000V respectively. The collector-electrode current increases with the aperture. Also, the collector current of the circular-shaped focus-gate FED structure is larger than that of the rectangular-shaped one.

4. CONCLUSIONS

We have applied our simulator to study the electrical performances of the circular-shaped and rectangular-shaped focus-gate FED structures. The dependence of the focus-gate characteristics of FED structures was investigated extensively. Results of the circular-shaped focus-gate FED structure are able to emit larger collector current than the rectangular-shaped one. By using circular-shaped focus-gate FED structure, the focusing characteristics of electron beam can be significantly improved.

ACKNOWLEDGMENT

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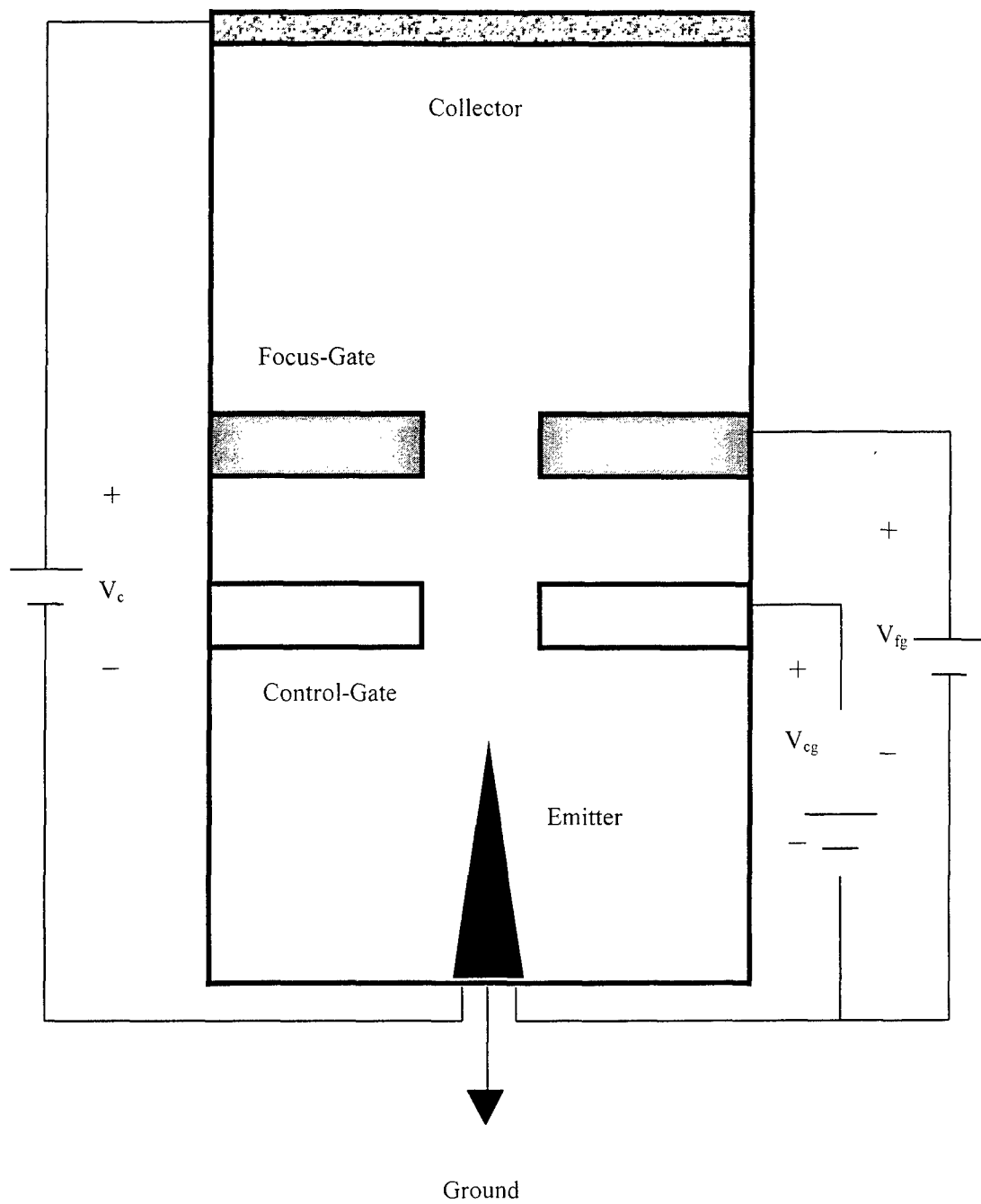
Fig. 1. Schematic diagram of the typical double-gate FED structure used in this article.
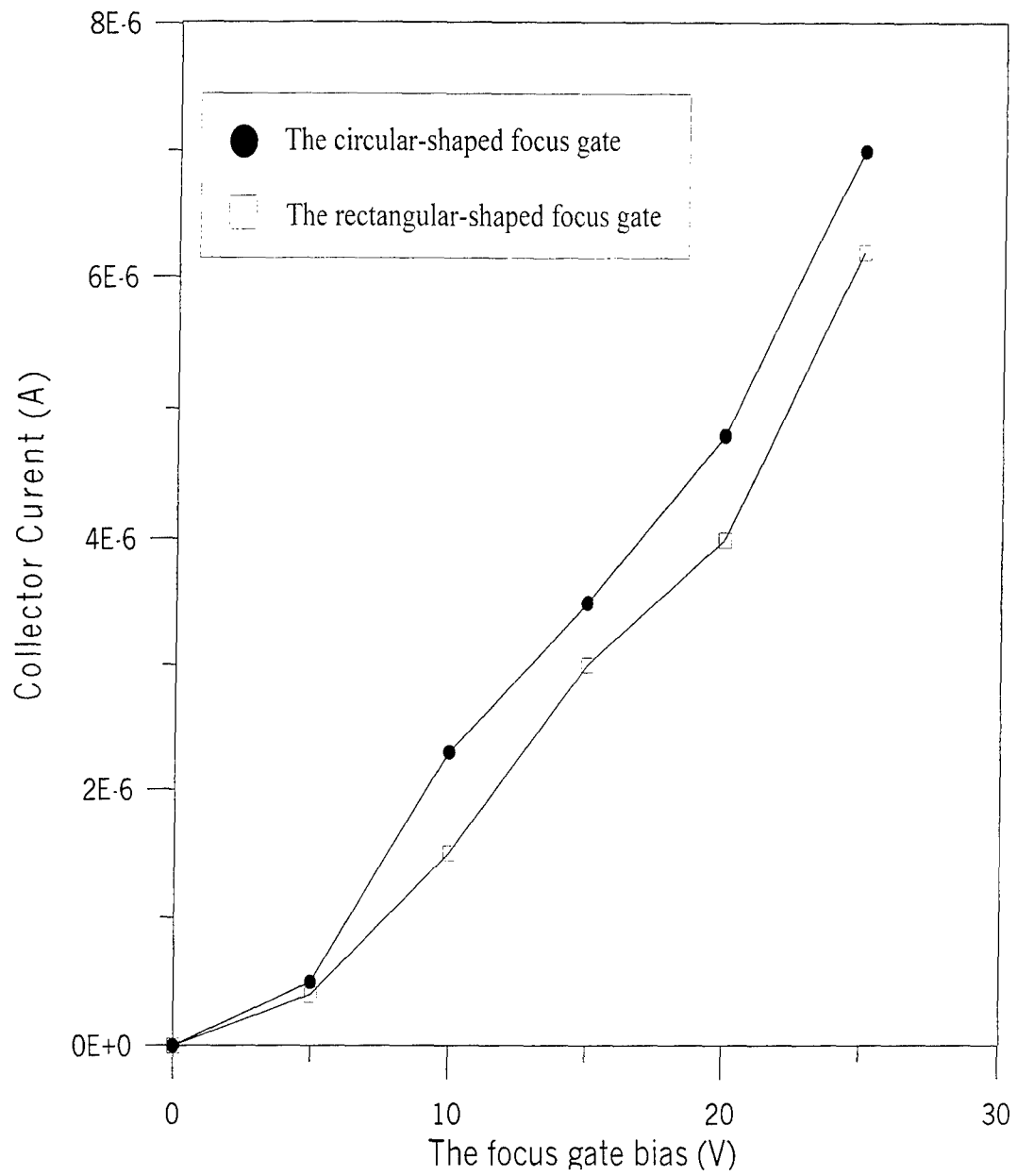
Fig. 2. The collector currents of the circular-shaped and rectangular-shaped focus-gate FED structures with different focus-gate bias. Where, the identical applied biases are V_{cg}=100V and V_c=1000V.
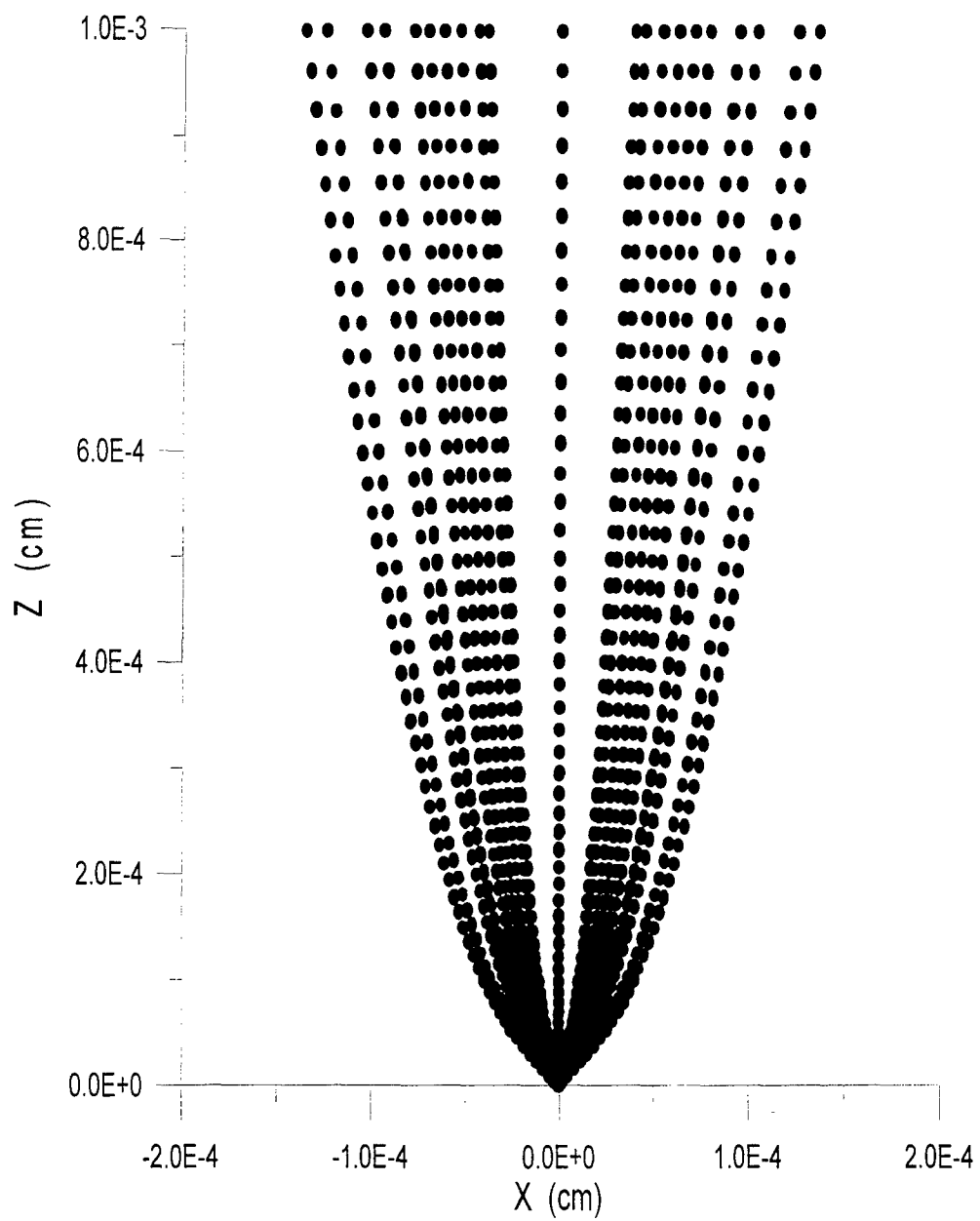
Fig. 3. (a) The simulated electron-trajectory results of the circular-shaped focus- gate of double-gate FED structure. Where, the applied biases are V_{cg}=100V, V_{fg}=30V, and V_c=1000V.
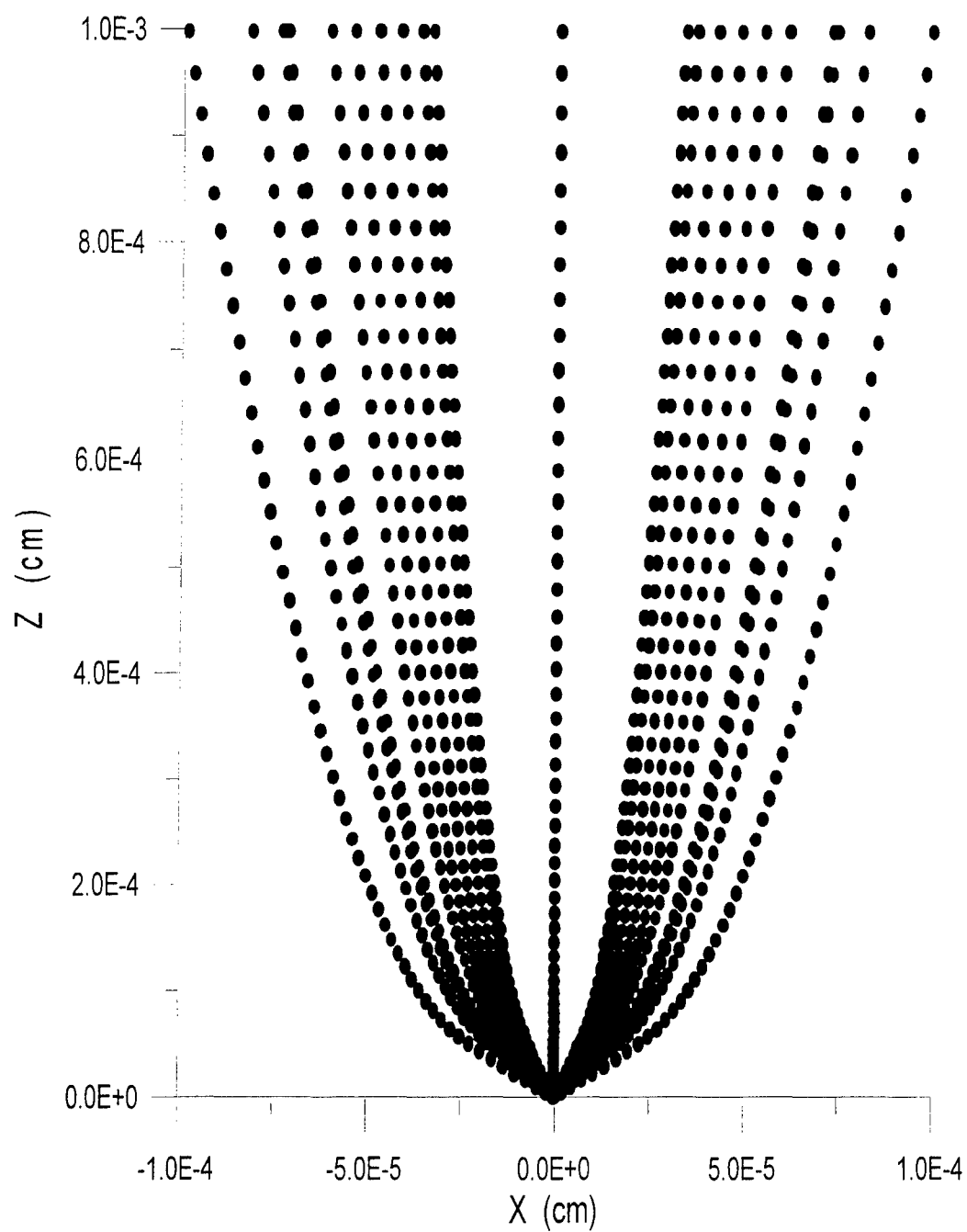
Fig. 3. (b) The simulated electron-trajectory results of the rectangular-shaped focus-gate of double-gate FED structure. Where, the applied biases are $V_{cg}=100V$, $V_{fg}=30V$, and $V_c=1000V$.
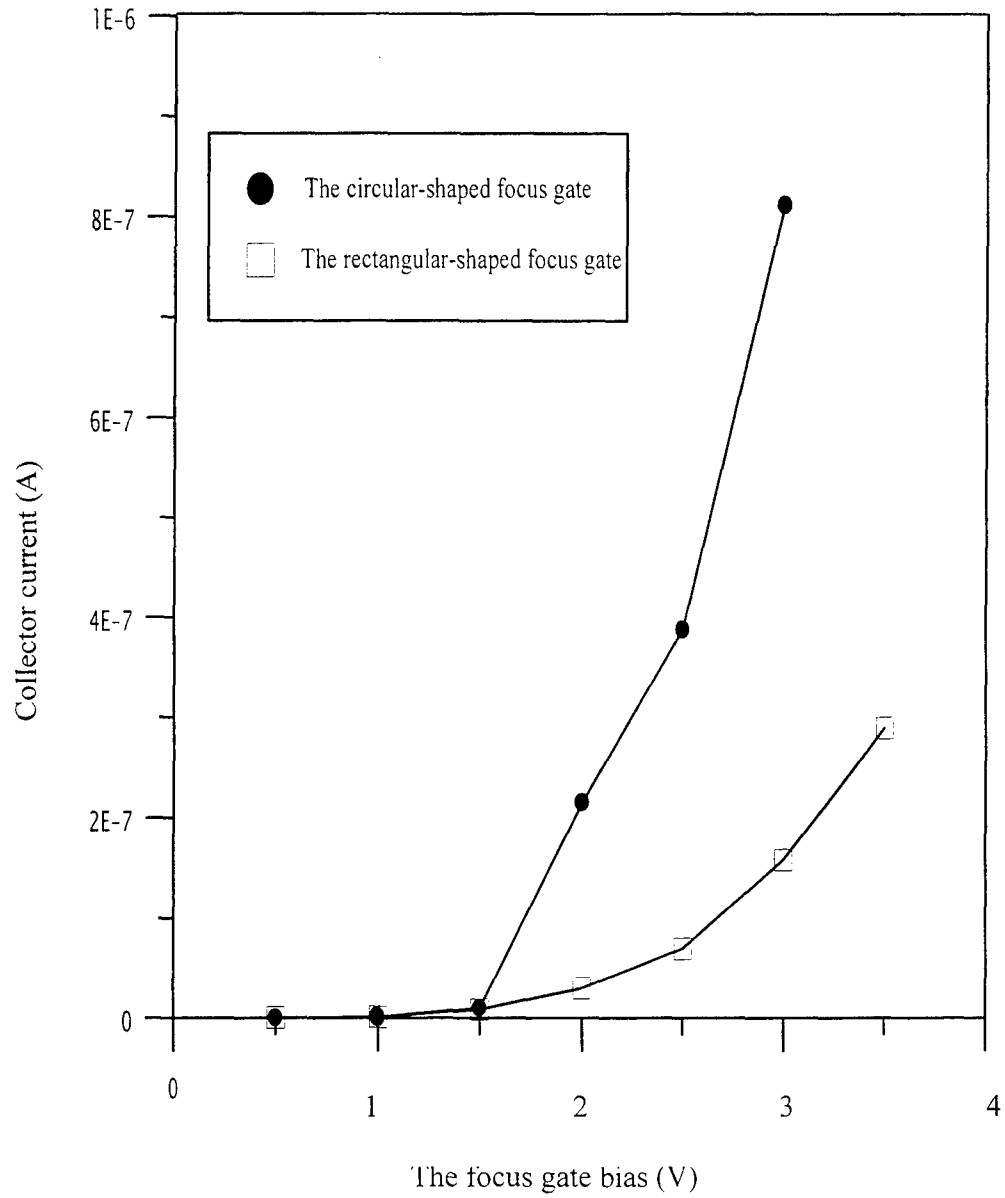
Fig. 4. The collector currents of the circular-shaped and rectangular-shaped focus-gate FED structure with different focus-gate aperture, where the identical applied biases are V_{cg}=100V, V_{fg}=10V, and V_c=1000V.